Narrow-Angle Astrometry with PTI and Keck Interferometer

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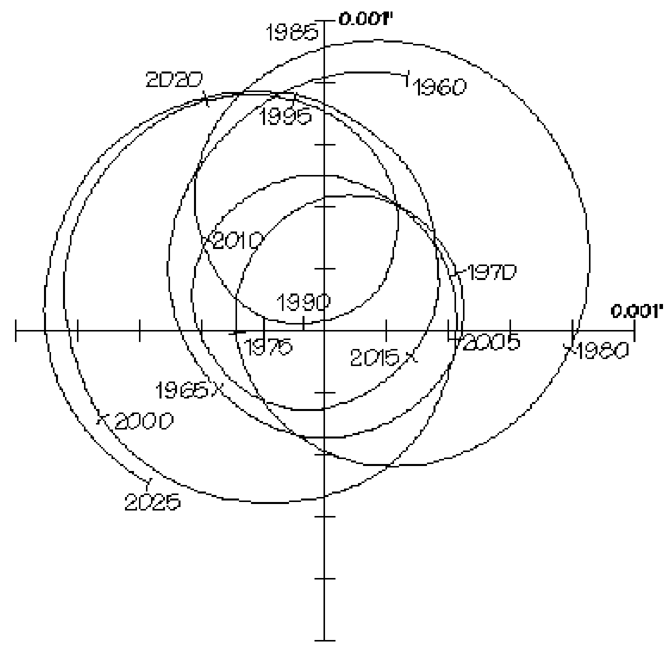
Outline

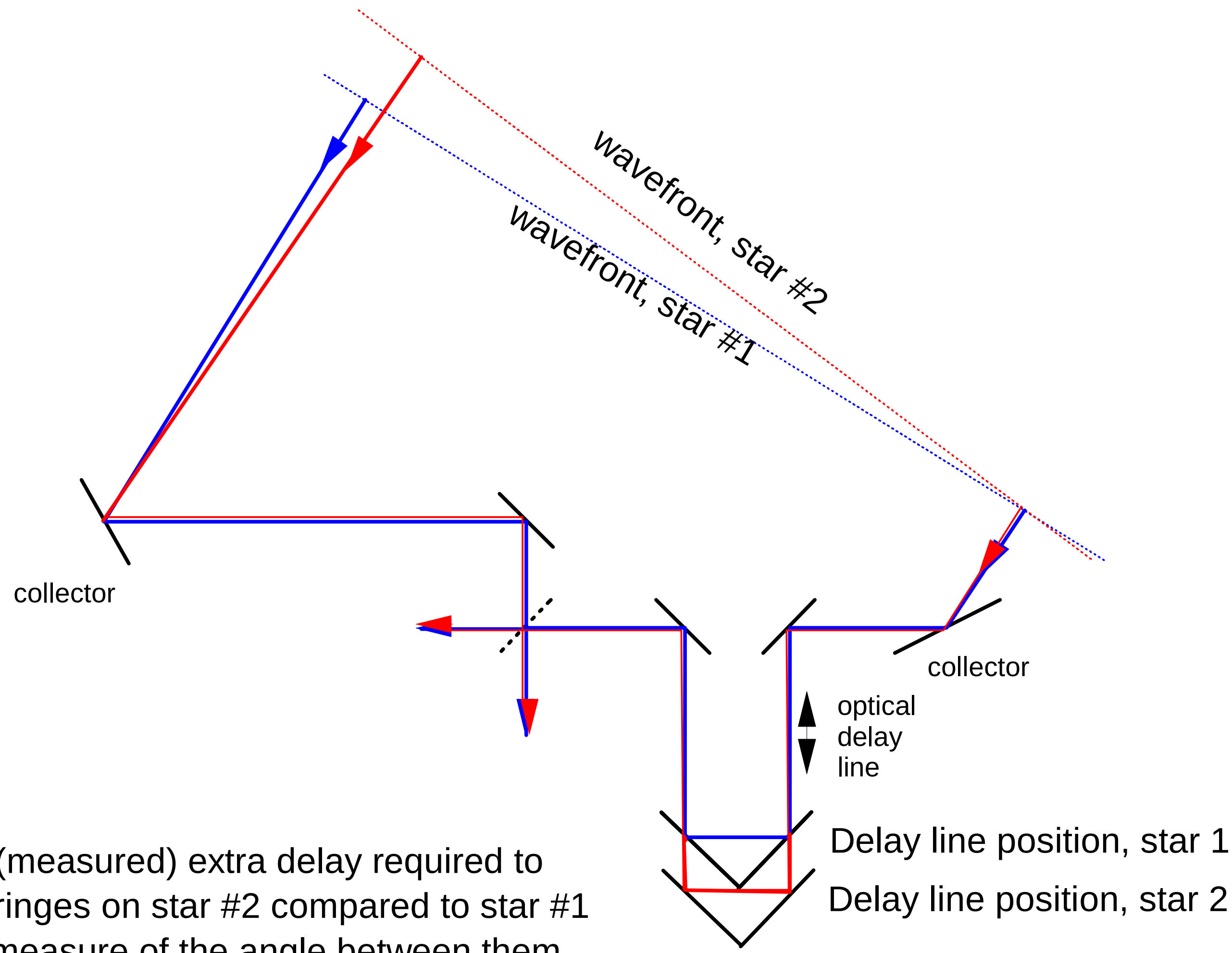
- Introduction
- Implementing narrow-angle astrometry with an interferometer
- Implementation at PTI - emphasis on components
- Implementation at Keck Interferometer - emphasis on error budget

Searching for exoplanets with narrow-angle astrometry

- Astrometry is a complementary technique to radial velocity
  - Senses transverse vs. longitudinal motion
  - Sensitive to all orbital inclinations
  - Canonical Jupiter/Sun signature:
    +/- 0.5 mas at 10 pc
- Required accuracy to conduct an interesting search
  < 50-100 uas
- Key feature of the measurement: Fundamentally narrow angle
  - Can use angularly-nearby references

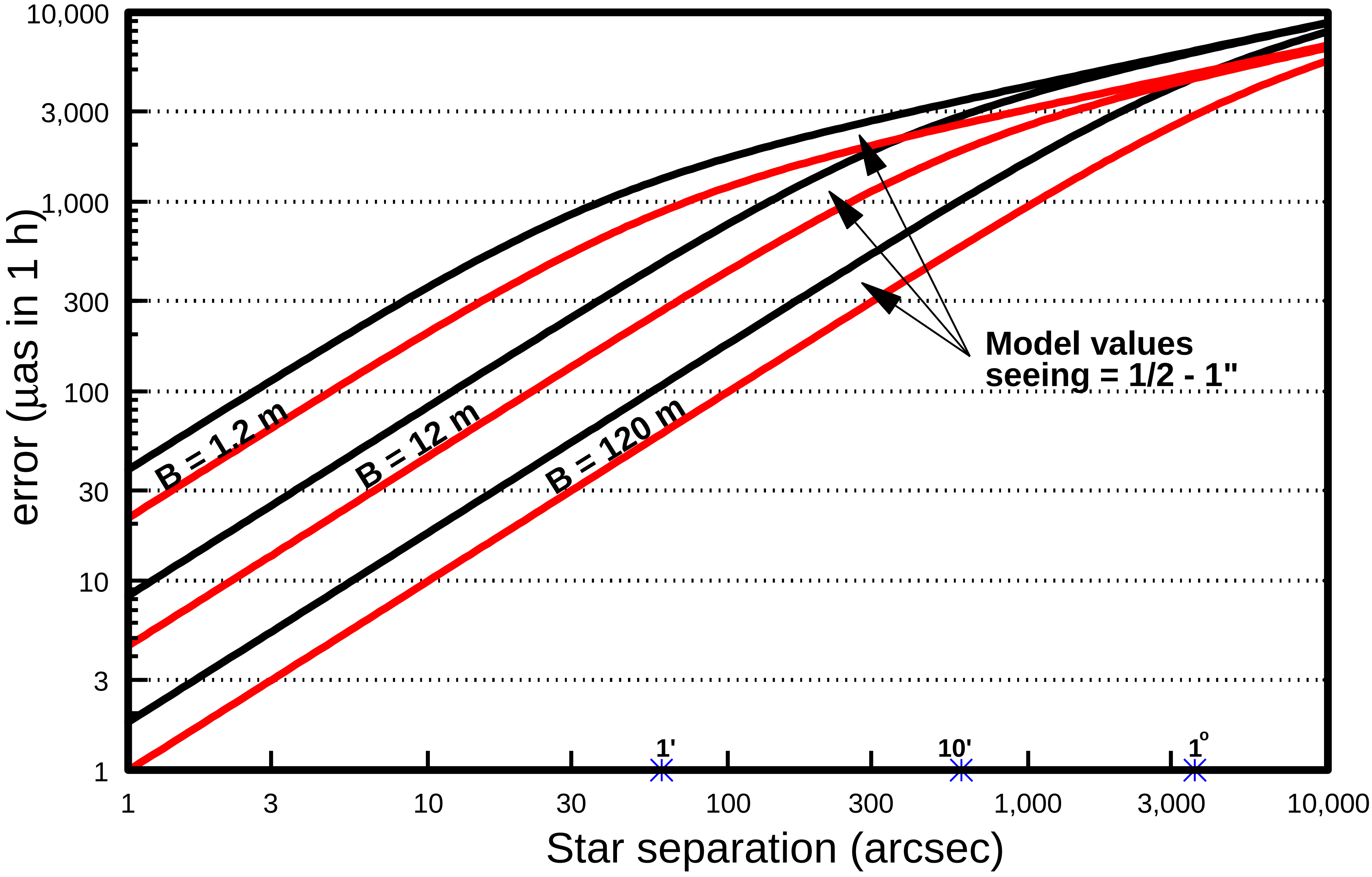


Differential astrometry with an interferometer



The (measured) extra delay required to get fringes on star #2 compared to star #1 is a measure of the angle between them

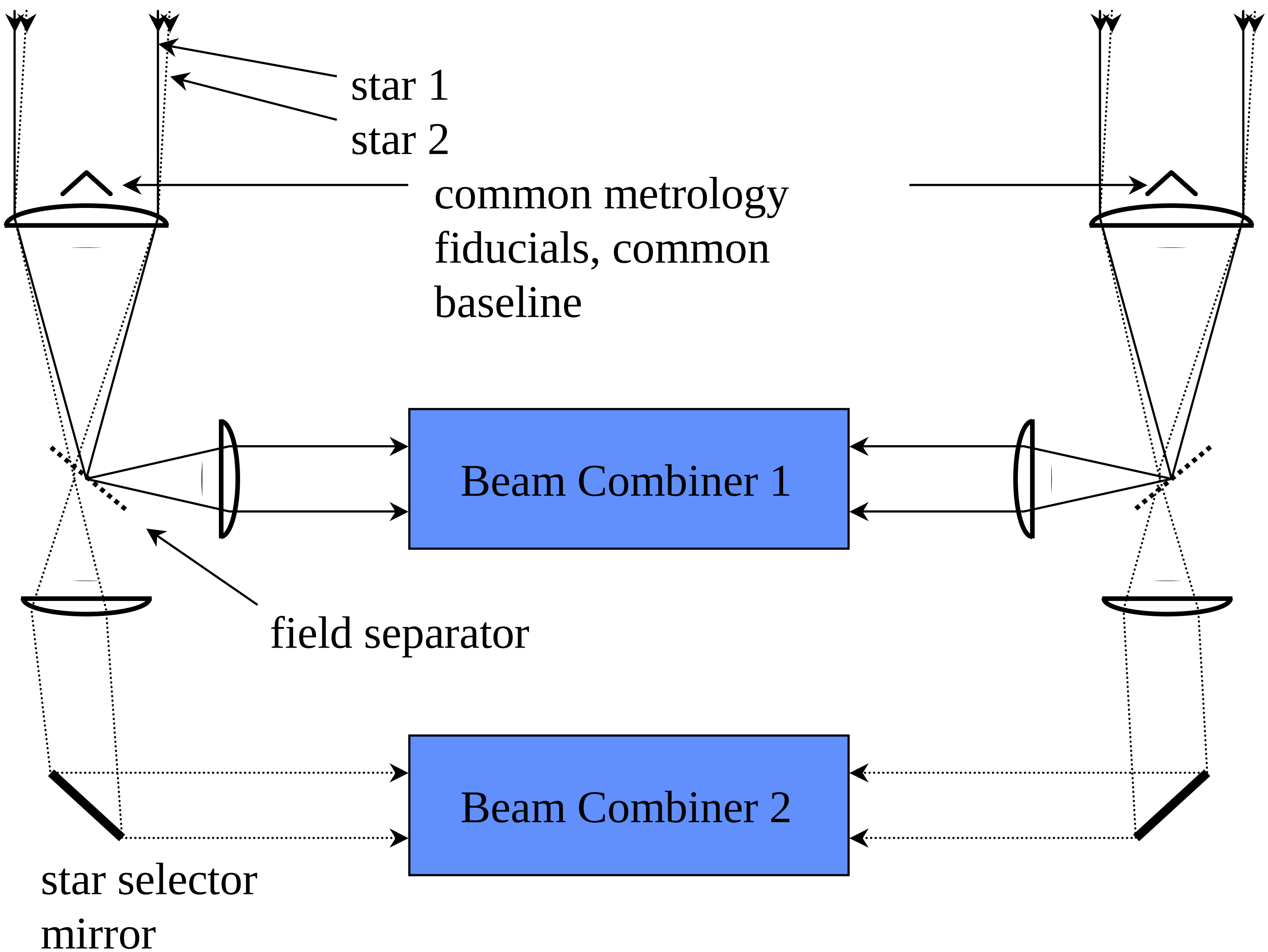
Atmospheric limits to a narrow-angle measurement



Implementing a narrow-angle measurement

- Measurement of the two stars must be essentially simultaneous to exploit the common-mode nature of the atmosphere over small fields
  - But…instantaneous interferometer field of view is typically only a few arcsec
- Measurements should use as many common optics as possible to minimize systematic errors
  - I.e., want to use the same basic interferometer to measure both stars
- One implementation: dual-star astrometry

Dual-star concept



Implementation, continued

- With the dual-star concept, the same baseline is used for the two stars
  - Delay equation: x = **B • s** + C; 4 instrument parameters
  - Baseline knowledge requirements (**B**; 3 parameters) are greatly reduced from those needed for an absolute measurement
- Laser metrology to common corner cubes monitors 4th parameter (a.k.a. constant term)
  - Laser metrology is at the full accuracy, but is a (relatively) straightforward linear measurement

Phase referencing

- In a small field, although the primary star will be bright (chosen to be nearby to maximize the astrometric signature), the secondary star will generally be faint and not trackable with short integration times
  - Use phase referencing to stabilize the optical path to allow long coherent integrations to increase sensitivity
- Phase referencing is the temporal analog of adaptive optics (AO)
  - AO
    - » AO uses a reference star (or laser guide star) to measure atmospheric wavefront distortions
    - » Uses a deformable mirror to correct distortion on reference star and in vicinity of reference star
  - Phase referencing
    - » Uses a reference star (the primary star in this case) to measure atmospheric fringe motion
    - » Uses an optical delay line to correct motion on reference star and in vicinity of reference star

Isoplanatic angle

- How close do the two stars need to be?
  Within the same isoplanatic patch
  - Within the isoplanatic patch the atmospheric effects on the stars are correlated (typically, OPD differences < 1 radian)
  - Isoplanatic angle = radius of isoplanatic patch
    - » $\theta_0 \sim 0.2 r_0 / h^*$, where h^* = effective height of turbulence
  - Isoplanatic angle improves with seeing and wavelength

Seeing	θ_0 at 0.55 um	θ_0 at 2.2 um
1 arcsec	2 arcsec	10 arcsec
0.5 arcsec	4 arcsec	20 arcsec

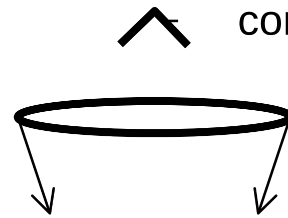
Implementation summary

- Two interferometers, sharing common baseline and apertures
- Two stars: one bright (target w/planet, nearby); one faint (astrometric reference w/ no planet (hopefully), far away)
- Use target star as phase reference
  - Cophase (phase reference) interferometer for stars within the isoplanatic patch of the target star
- Chose astrometric reference star within isoplanatic patch of target star
- Work in the infrared (2.2 um) for its larger isoplanatic angle
  - Increases solid angle over which to find astrometric reference stars (~20 arcsec radius)
  - Allows use of larger apertures (1.5 - 2.0 m with tip/tilt correction) to increase sensitivity
    - » Combination allows good sky coverage
- Potential accuracy with 100-m baseline is tens of uas in an hour integration

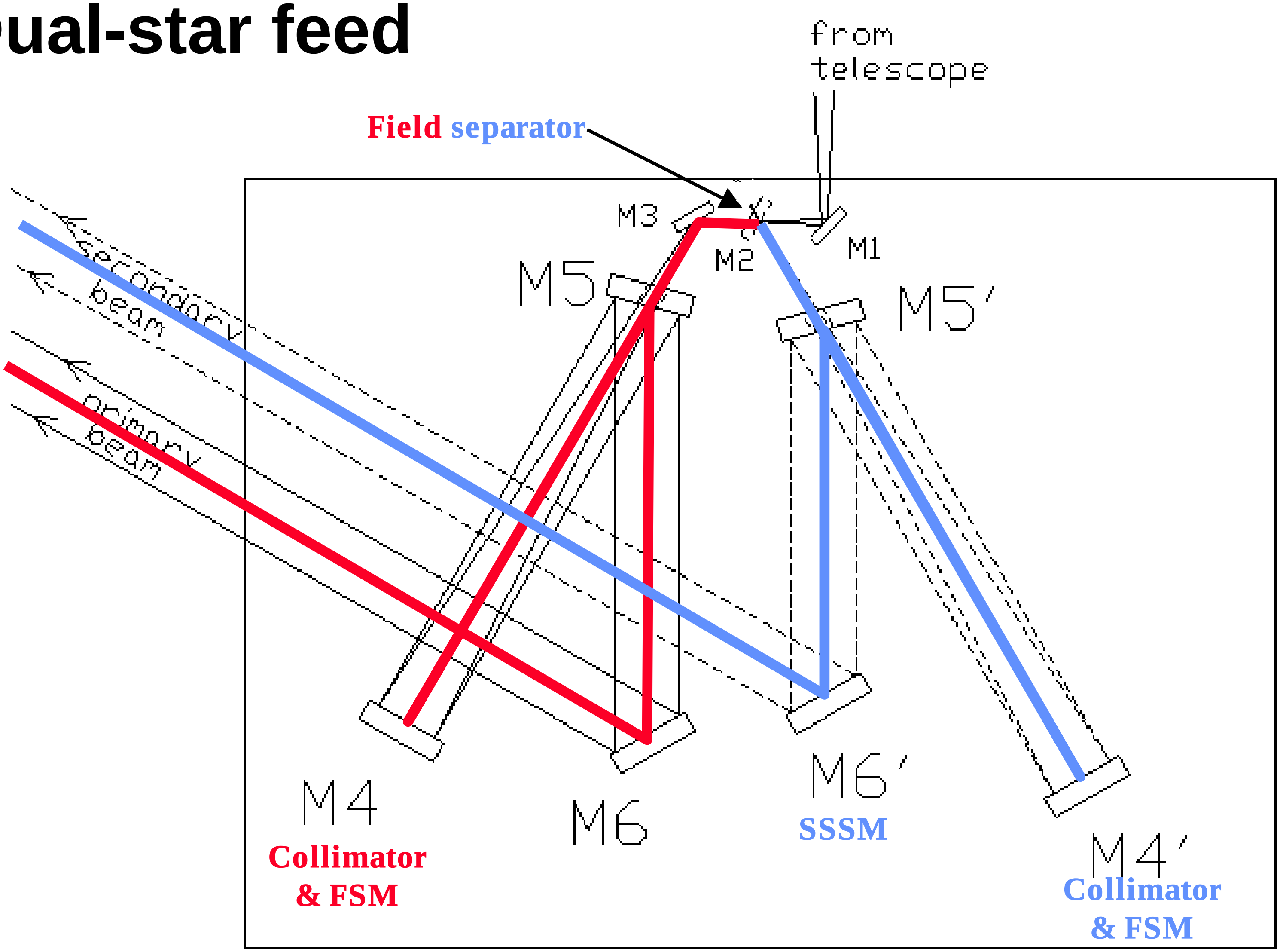
Palomar Testbed Interferometer

- NASA funded, tech development for Keck and other interferometers
- 2-way system, 110 m max baseline
- 40 cm collecting apertures
- Active broadband fringe tracking at K (2-2.4 μm) or H (1.5-1.8 μm)
- Spectrometer resolution of R = 25 – 50
- Angle tracking at R+I (0.7 – 1.0 μm)
- Dual-star capability for narrow-angle astrometry

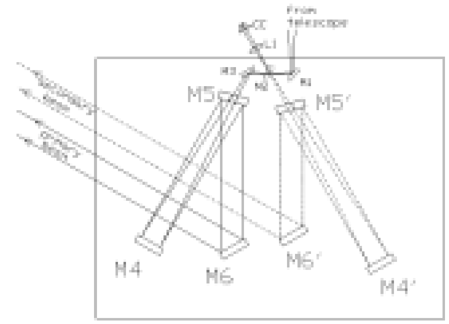
More detail:
ApJ 510, 505 (1999)



Dual-star feed

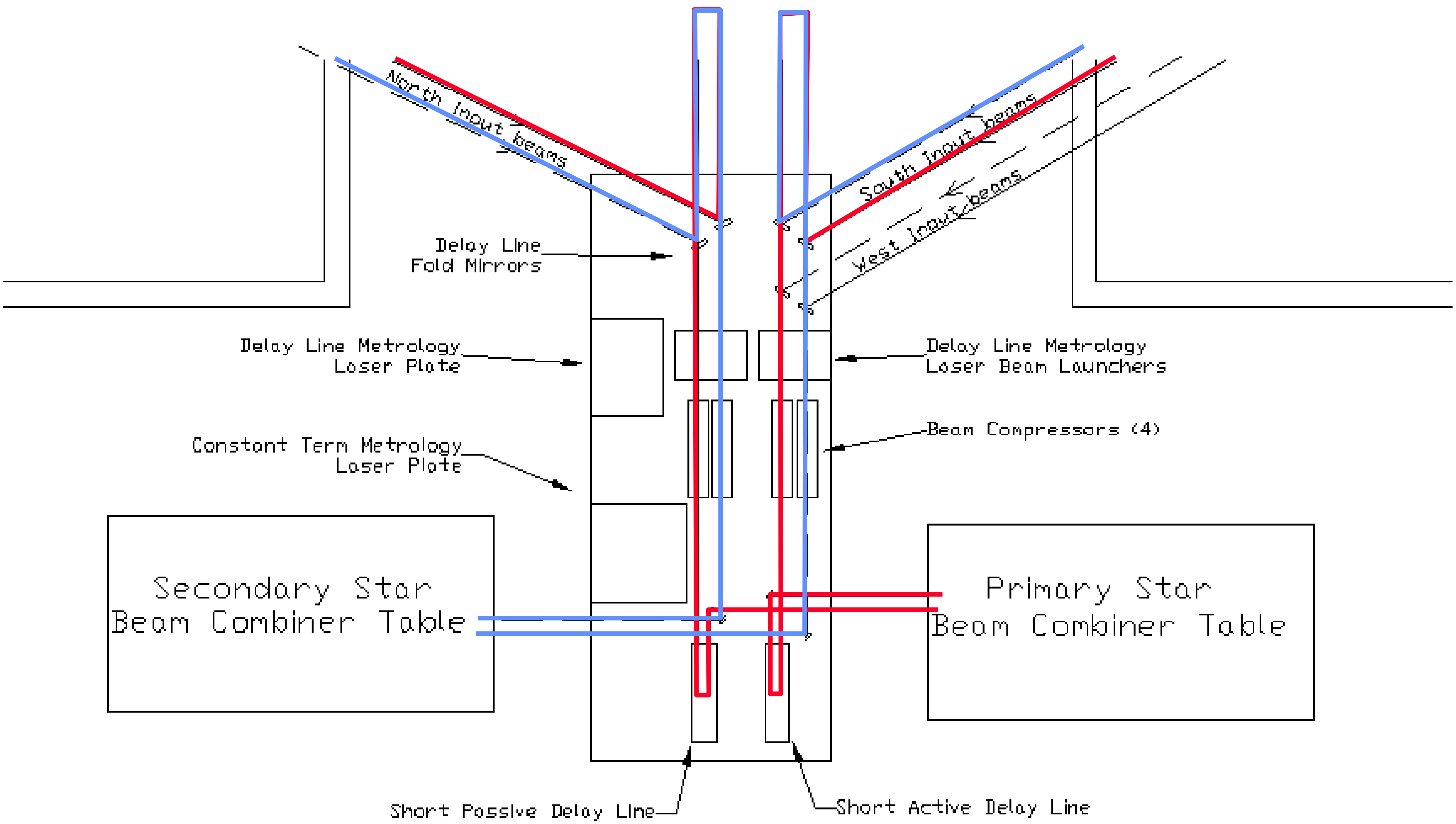


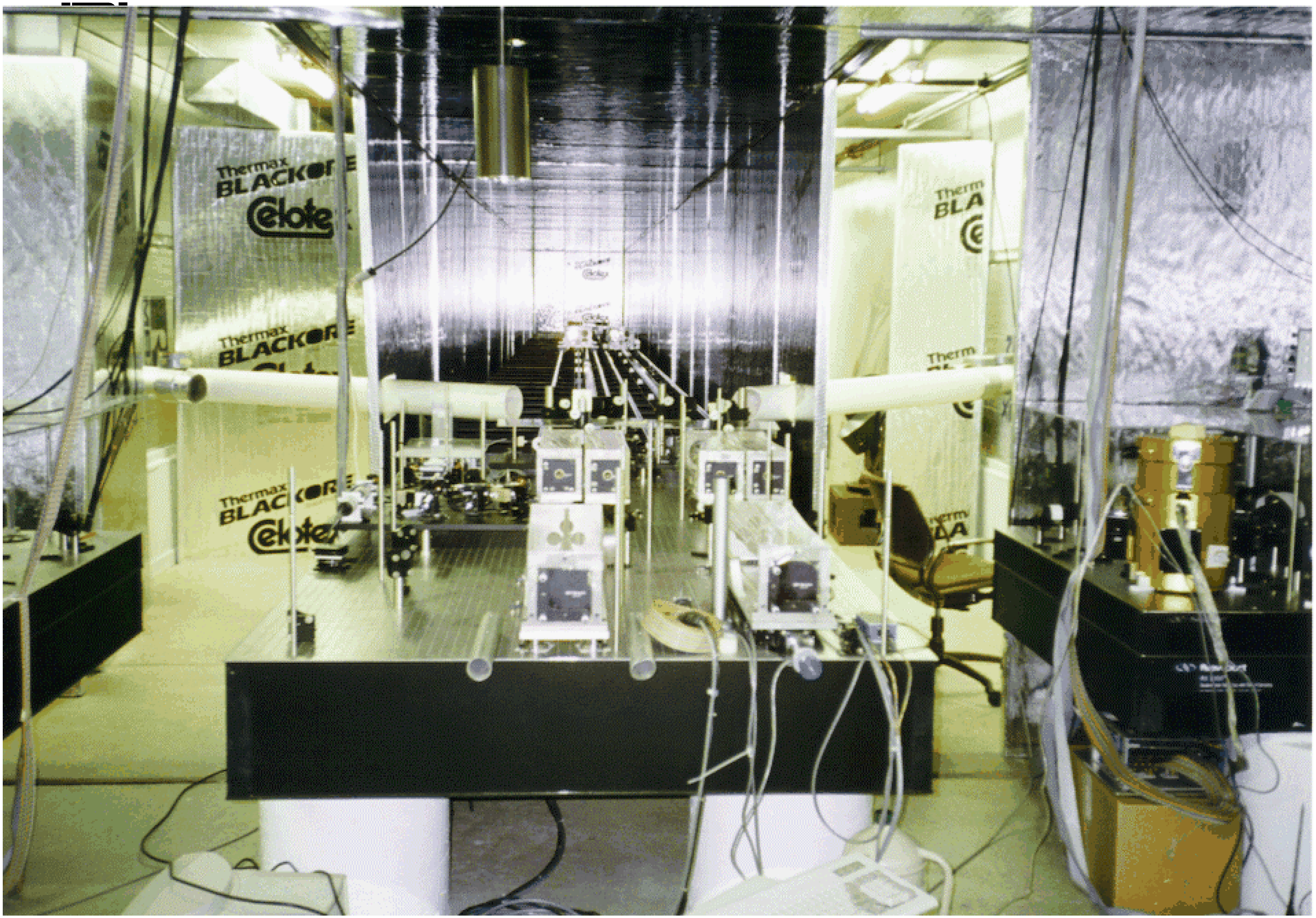
Dual-star feed



- Separates light from telescope into two separate collimated beams
  - Field is split by field separator (M2)
  - Primary beam recollimated by M4, directed to building by M5, M6
  - Secondary beam recollimated by M4'
    - » M6', the secondary star selector mirror (SSSM) is located at an image of the entrance pupil
    - » Steering the SSSM selects the secondary star within the siderostat field-of-view

Central optics




Thermax
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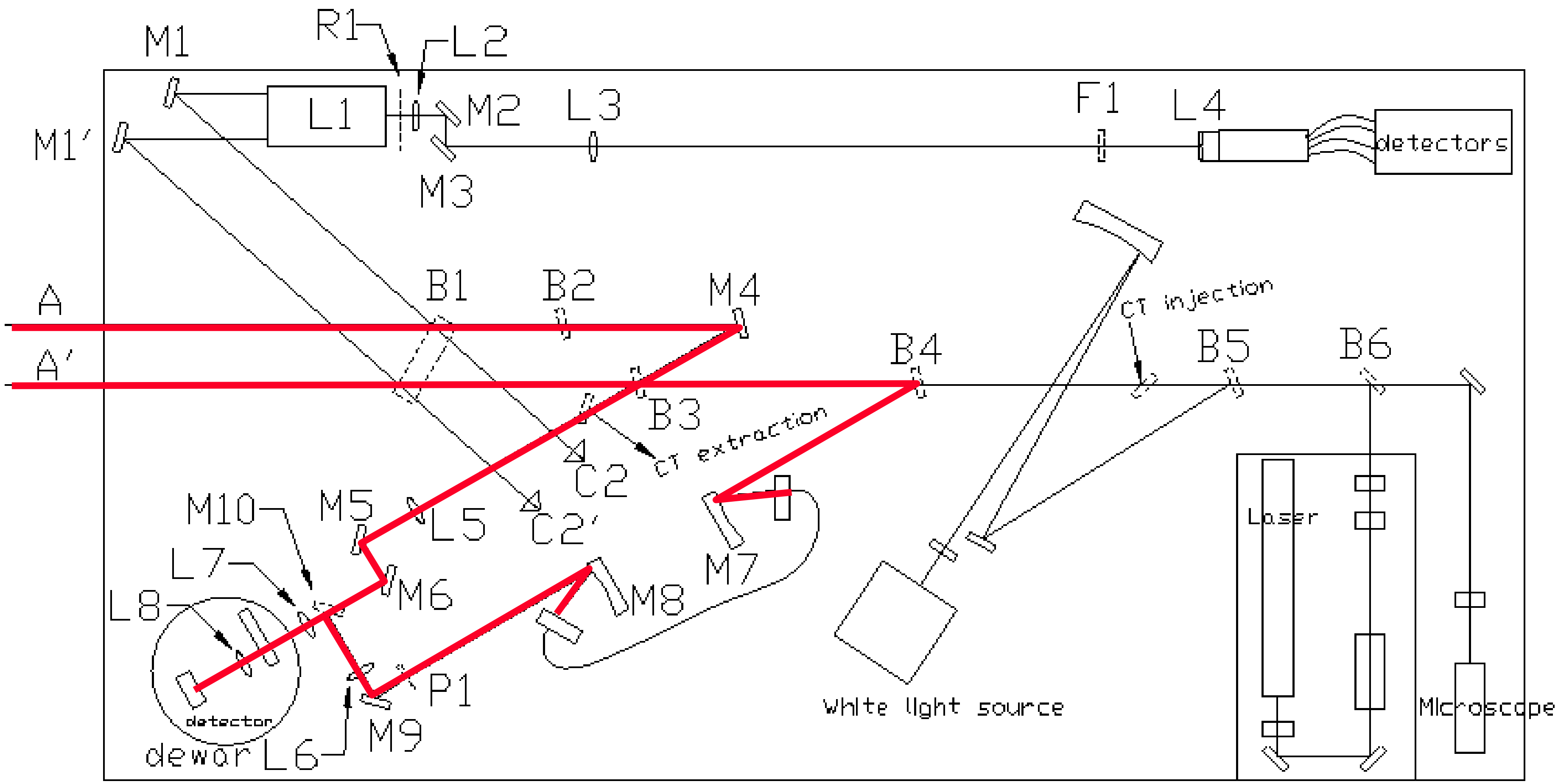
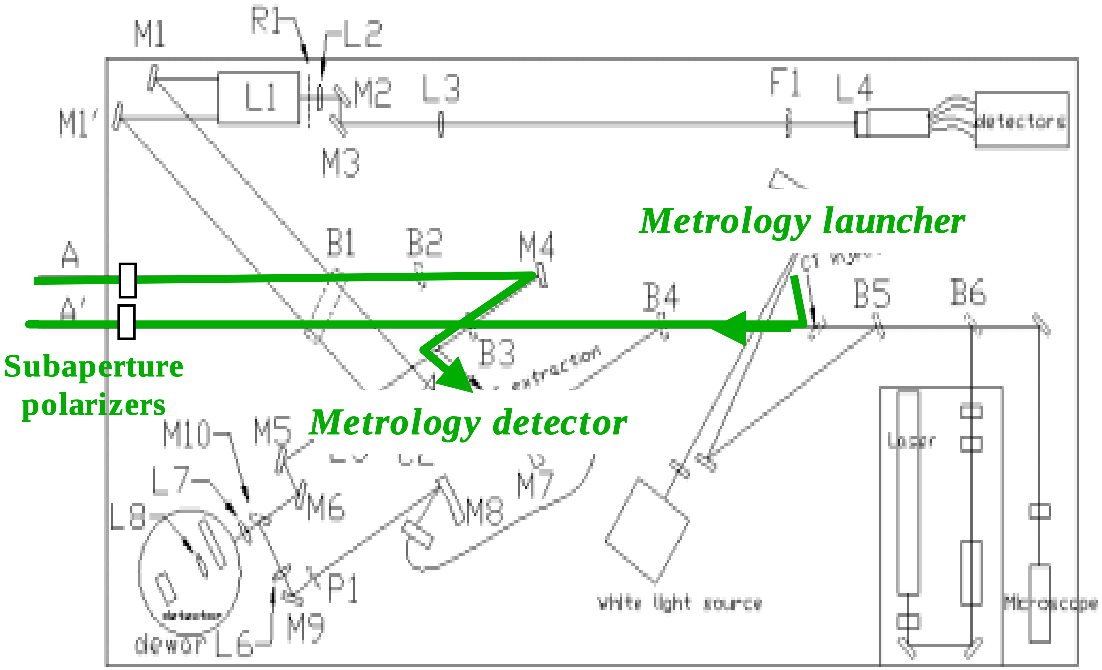
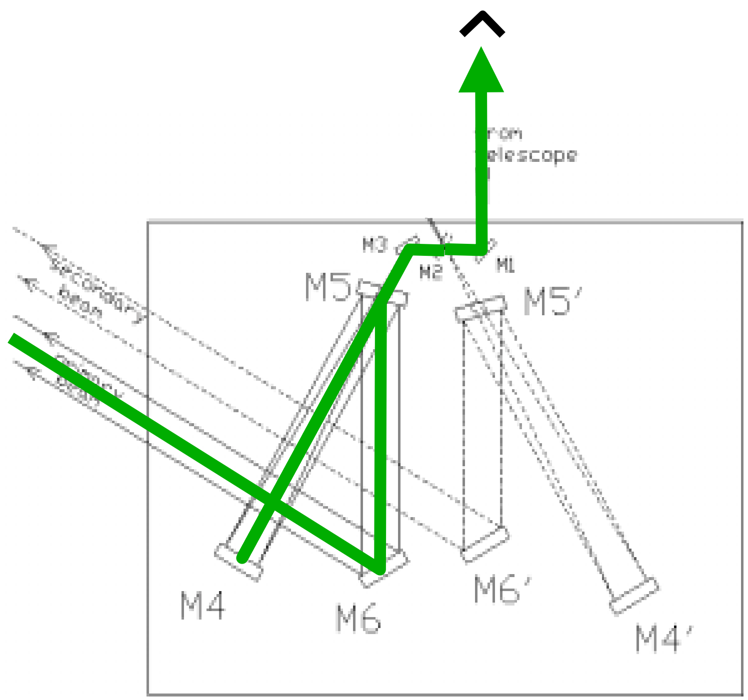
Fringe tracker optics



Constant-term metrology

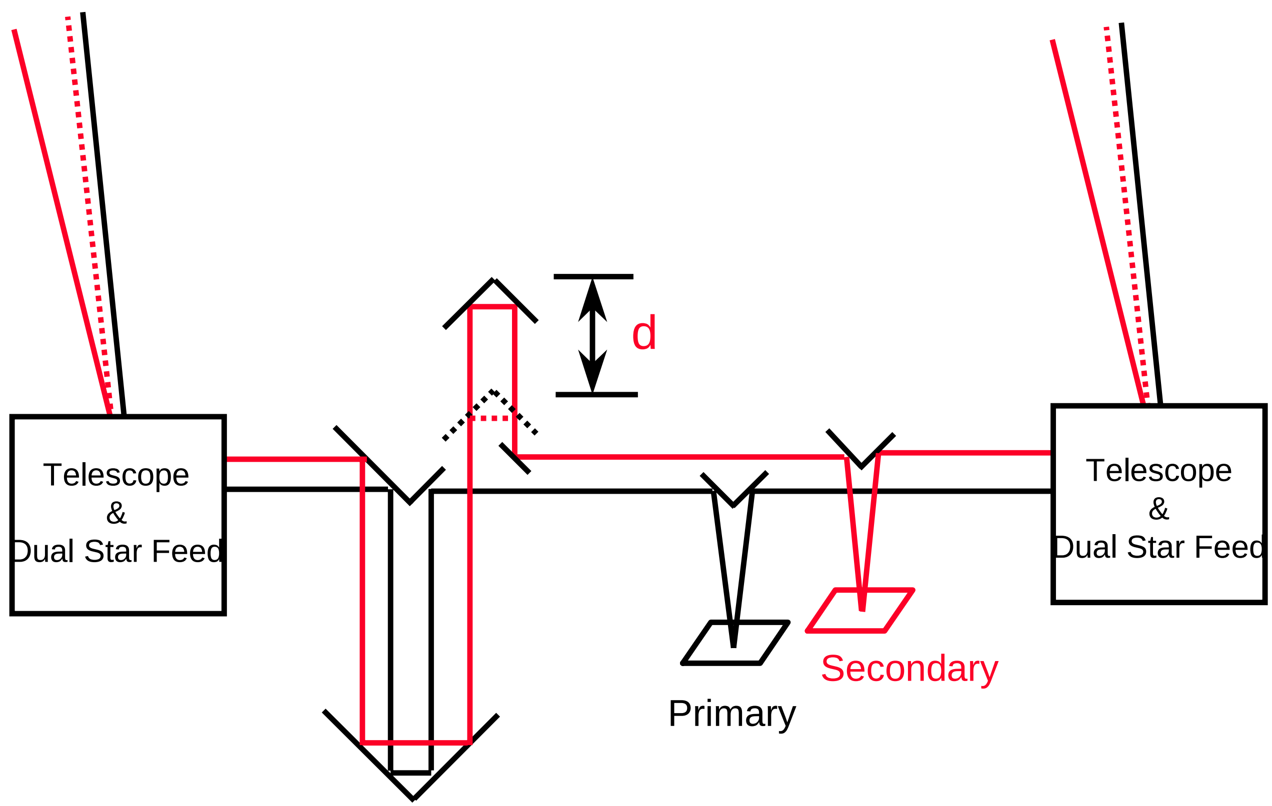




Constant-term metrology

- Measures difference in optical paths between the two arms for each beam combiner
  - Difference in metrology measurements between the two beam combiners, plus difference in fringe phases, gives star separation
- Heterodyne metrology starting at main beamsplitter to corner cubes at the telescopes
  - Subaperture polarizers send *s* and *p* polarizations to different arms
  - Heterodyne at separate carriers to avoid interference between primary and secondary metrology systems

Making a narrow-angle measurement

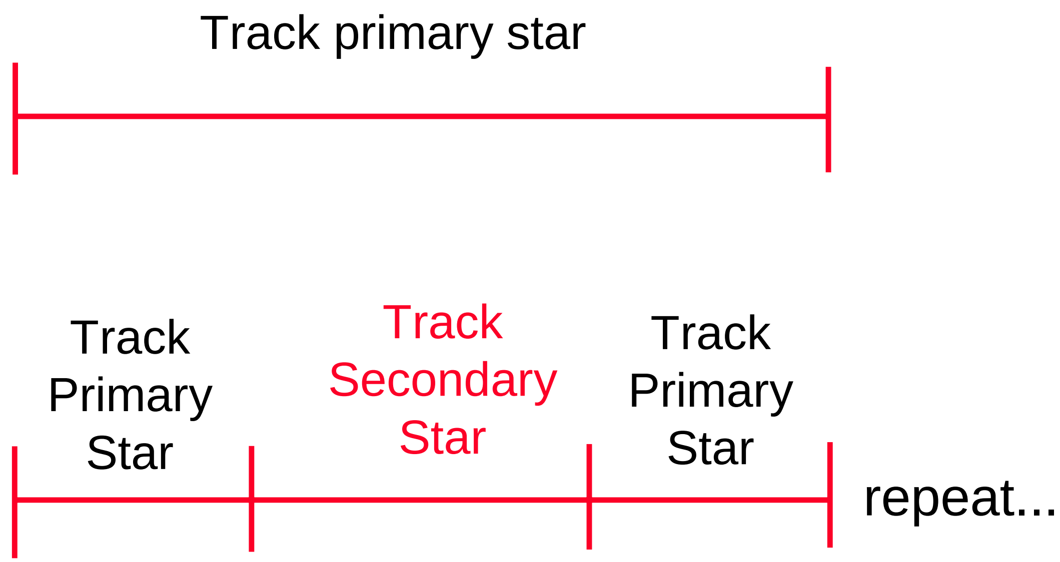


Differential delay line shown in secondary path for clarity

Astrometry Observation

Primary Combiner
(phase reference only)

Secondary Combiner
(chops between primary
and secondary)

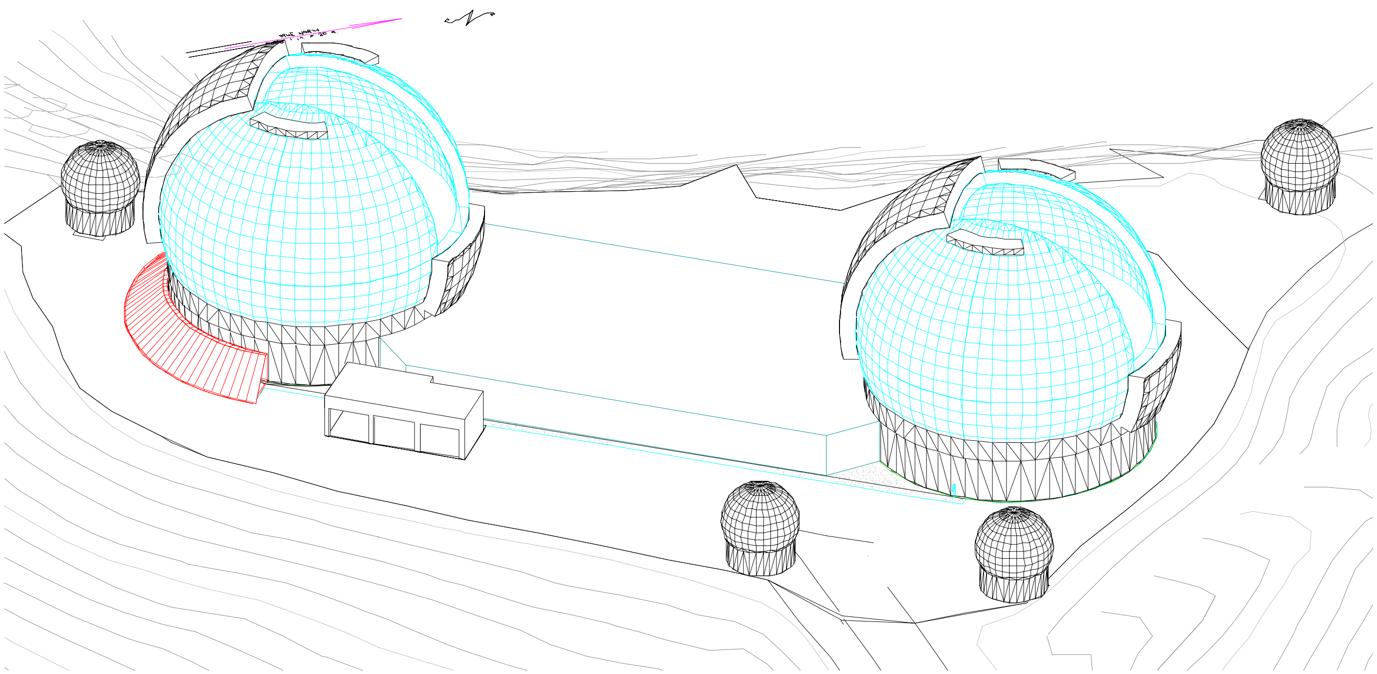


Delays: x_{p0} x_s x_{p1}

- With this implementation, the primary combiner need only be stable, and no special matching is required between the primary and secondary combiners
- "Astrometric quantity" : $\Delta x = x_s - ½(x_{p0} + x_p)$

Keck Interferometer

- Interferometry with the two 10-m Keck telescopes on Mauna Kea and four 1.8-m outrigger telescopes
- NASA-funded joint project between JPL and CARA
- Broad range of science capabilities

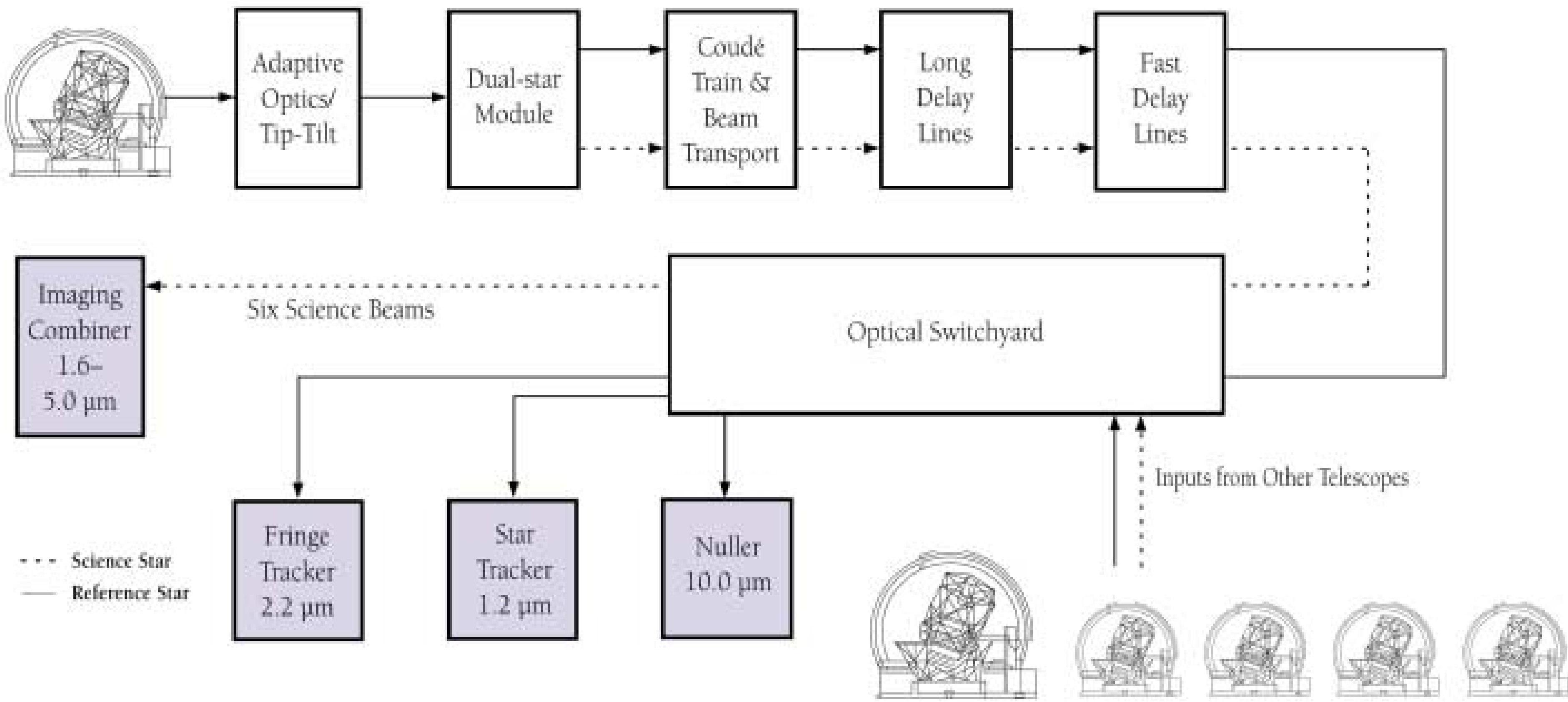


Key Features

- Michelson combination among the two 10-m Kecks and four 1.8-m outrigger telescopes
  - Keck-Keck baseline: 85 m
  - Outrigger-outrigger baseline: 30 m (min) / 135 m (max)
- Phasing with adaptive optics and fast tip/tilt correction
- Cophasing with fringe detection/tracking and active delay lines
  - Dual-star feeds at each telescope
- Back-end instruments
  - Two-way beam combiners at 1.5 - 2.4 μm for fringe tracking (cophasing), astrometry, and imaging
  - Multi-way imaging combiner at 1.6 - 5 μm
  - Nulling combiner at 10 μm

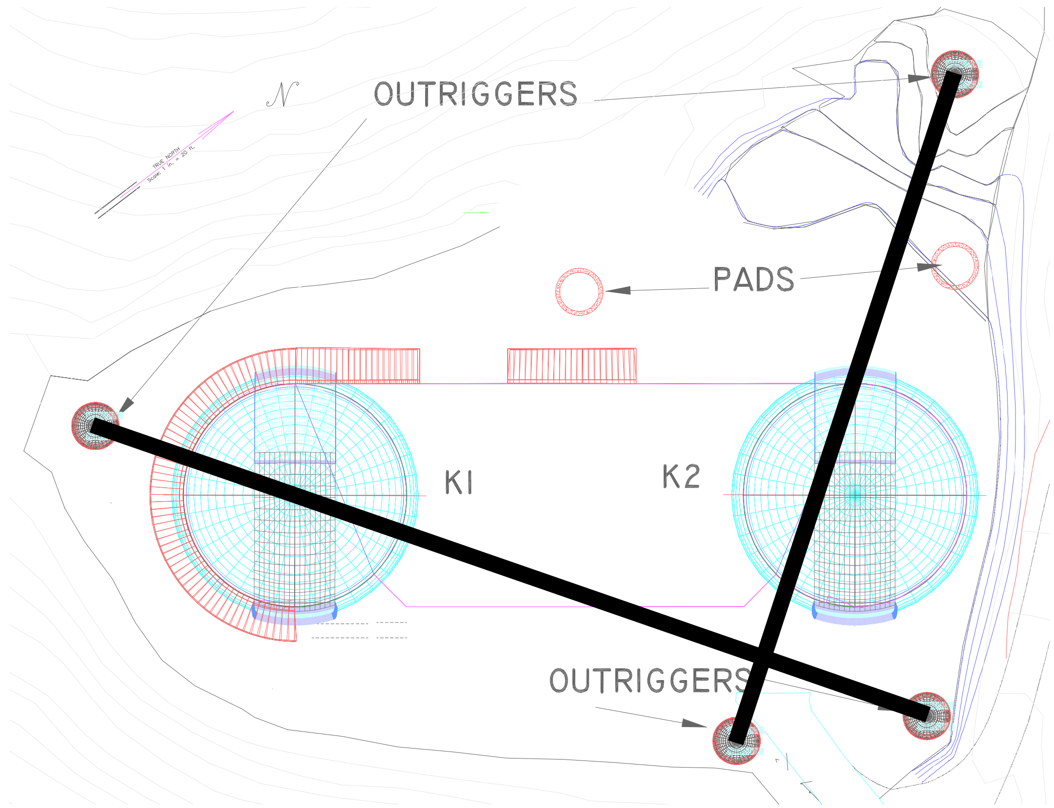
JPL

Keck Interferometer Beam Train



Astrometry Implementation

- Configuration
  - 4 1.8-m outrigger telescopes
  - Orthogonal >100m baselines
  - Cophased interferometer architecture at 2.2 um
  - Dual star feeds
  - End-to-end laser metrology
  - 30 uas•sqrt(hr) accuracy for differential astrometry



Astrometry Error Budget

- Contributors to astrometry error budget
  - Measurement noise on secondary star
    - » This will generally limit performance to ~30 uas•sqrt(hr)
  - Atmosphere
    - » With 100-m baseline, 15” mean star separation, 100 m outer scale, good seeing, expect ~10 uas•sqrt(hr)
  - Instrument systematics
    - » Limit to 10 uas•sqrt(hr)
    - » Includes terms associated with the baseline **B** and the constant term C

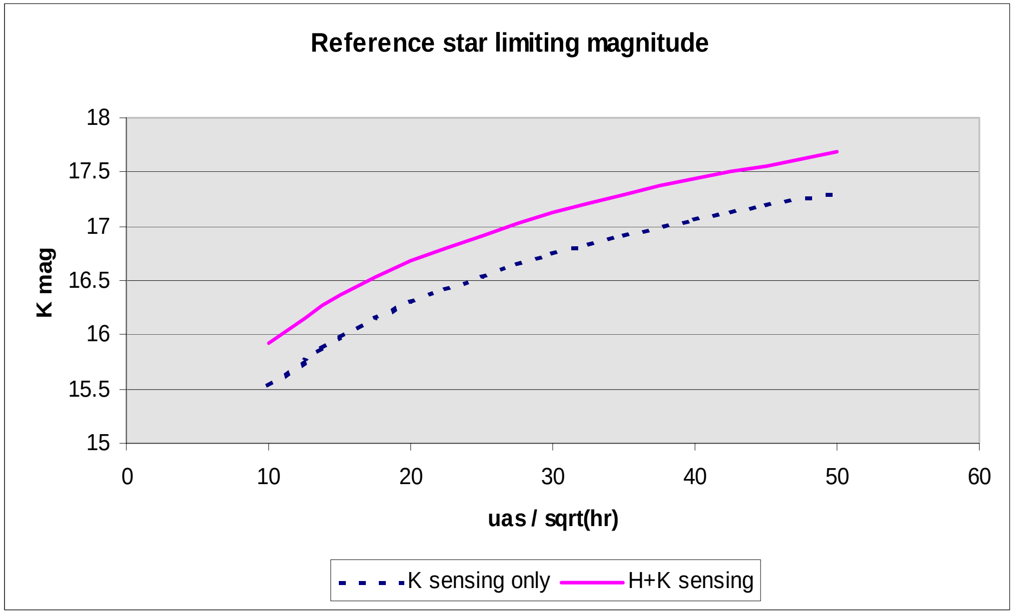
Astrometric reference star measurement noise

- Astrometric error given by

$$\Theta = \frac{\lambda}{2\pi B}\frac{\sqrt{2}}{\mathrm{SNR}},$$

where

$$\mathrm{SNR}^2{}_{\mathrm{BLIP}} = 0.81 \times \frac{4 N_1 N_2 V^2}{B_1 + B_2} \text{ (Total SNR)}$$



- Measurement noise < 30 uas / hr for K<17.1

Astrometry systematics error budget

			nm per arm	nm total	uas total	
unmodeled pivot noise	25.0	um	1.9	2.7	5.5	
pivot beacon to pivot transfer	25.0	um	1.9	2.7	5.5	
DSM CC to beacon transfer	25.0	um	1.9	2.7	5.5	
baseline solution	35.0	um		2.6	5.4	
DCR					5.0	
beamwalk of secondary over field			2.5	3.5	7.3	
alignment of metrology to starlight	0.5	arc sec	1.8	2.5	5.2	
alignment drift	0.5	arc sec	1.8	2.5	5.2	
metrology stability	1.00E-08	fractional	0.1	0.1	0.2	
metrology polarizer mount gradient	0.04	K	2.0	2.8	5.8	
fringe-measurement accuracy	0.005	rads	1.8	2.5	5.1	
beamwalk stability in propagation	1.5	mm	2.3	3.2	6.6	
				TOTAL:	**18.8**	**uas**

Systematics in the baseline

- Because of narrow-angle nature of measurement, baseline knowledge requirements get reduced by size of field
  - For wide angle astrometry, a 25 um pivot error at each end point of a 100 m baseline would introduce a 73 mas error
  - For 15” (0.07 mrad) mean star separation, error in a differential measurement is only 5 uas
- Pivot error is allocated in the telescope among
    - » Offset between azimuth and elevation axes
    - » Offset between tertiary surface and elevation axis
    - » Offset of the pivot with respect to the foundation
  - We are mostly concerned with residuals after simple modeling

Subtleties on Pivots/Baselines

- The effective pivot for narrow-angle astrometry is not necessarily the same as the pivot for wide-angle astrometry
  - For wide-angle astrometry, the entire telescope is repointed between targets
  - For narrow-angle astrometry, the telescope is stationary, and repointing between primary and secondary stars is accomplished by tilting a field-steering mirror in the DSM
    - » Narrow-angle pivot is related to projection of the common corner cube through the telescope
  - Keck Interferometer will have monitors for the wide-angle pivot of the telescope, as well as a monitor to tie the wide- and narrow-angle pivots together

Systematics in the constant term

- Beamwalk
  - – The metrology beam will typically be a pencil beam in the center of the starlight beam
    - » Each beam sees a slightly different OPD due to different averaging over imperfect mirror surfaces
      - If this is constant, it drops out
  - – As the star selector mirror rotates, the starlight and metrology beams will walk (translate) across some optics
    - » The changing footprints (and OPDs) can introduce systematic errors
- More mundane systematics
  - – Metrology pointing errors
  - – Thermal stability of non-common starlight/metrology optics
  - – Laser stability, etc.

Atmospheric dispersion errors

- The fundamental astrometric measurement is made by switching between primary to secondary stars on the same beam combiner
  - No matching of primary and secondary combiners is needed
  - Use of narrow spectral channels minimizes first-order color-dependent errors
    - Allows calibration of spectral-slope effects
- Monitoring of P, T to compensate for differential air delay effects

Conclusion

- Dual-star approach allows a simultaneous differential measurement with a long baseline interferometer
- Key concepts
  - Phase referencing, isoplanatic angle, IR operation
- Key pieces
  - Dual-star module, common corner cubes, end-to-end laser metrology
- Aspects of error budget
  - Baseline terms, linear terms
- Contributors
  - Photon noise, atmospheric noise, systematics
- PTI: technology development for Keck Interferometer
- Keck Interferometer: use the Outrigger telescopes and lessons from PTI to implement production astrometric measurements